Jongho Yoon
Department of Architectural Engineering,
Hanbat National University,
Taejon, 305-719, Korea

E. J. Lee
Division of New and Renewable
Energy Research,
Korea Institute of Energy Research,
Taejon, 305-343, Korea

D. E. Claridge
Mechanical Engineering Department,
Texas A&M University,
College Station, Texas 77843-3123
e-mail: claridge@esl.tamu.edu

Calibration Procedure for Energy Performance Simulation of a Commercial Building

Calibration of an energy simulation with actual data has generally been considered too difficult to be part of the energy audit procedure. The purpose of this paper is to develop a systematic method using a "base load analysis approach" to calibrate a building energy performance model with a combination of monthly utility billing data and sub-metered data such as is commonly available in large buildings in Korea. The calibration procedure was specifically developed to be suitable for use in both the audit and savings determination procedure within a retrofit process. The procedure has been visualized using a logical flow chart and demonstrated using the simulation of a 26-story commercial building located in Seoul as a case study. The results indicate that the approach developed provided a reliable and accurate simulation of the monthly and annual building energy requirements of the case study building. [DOI: 10.1115/1.1564076]

Introduction

A reliable calibration procedure is a key element in the use of computer simulation to accurately evaluate energy conservation measures (ECMs) and energy conservation opportunities (ECOs) for existing buildings. The calibration process compares the results of the simulation with measured data and *tunes* the simulation until its results closely match the measured data. Systematic calibration of building models has been reported by a number of researchers [1–4]. A post processor program has been developed to use data visualization as part of the calibration process [5]. Recent research on the calibration process has focused on comparing hourly measured data with simulation because the results represent the building dynamic energy characteristics in a more accurate and reliable way [6–9]. Others have calibrated simulations based on the ASHRAE simplified energy analysis method to daily data [10,11], but have aggregated the daily data from hourly data. The additional expense of the data loggers required to measure the hourly data has limited the number of buildings for which this data is currently available. Reddy et al. [12] calibrated a simulation to measured hourly heating and cooling coil loads to determine retrofit savings. Most of the early efforts calibrated the simulation results to the monthly utility bills for electricity and gas. However, there are typically more simulation inputs that can be varied than measured data points. This severely limits accurate calibration, and there is no standard way of calibrating the computer models of building energy performance to monthly data. Most large buildings in Korea have a dozen or more electric submeters in addition to the main service entrance. These meters are typically read monthly, but can be read daily for a short period to aid in calibration. This provides a much richer data source for calibrating a simulation than a single meter.

Therefore, the objective of this paper is to develop a calibration methodology for large commercial buildings based on the use of sub-metered monthly and daily data, which can be readily obtained for most large buildings in Korea, and perhaps for significant buildings elsewhere. The calibration procedure was specifically developed to be suitable for use in both the audit and savings determination procedure within the national retrofit program in Korea. The building type investigated in this study is the high rise office building with electric consumption for cooling and gas consumption for heating. The calibrated simulation model may then be used in energy audits to evaluate energy conservation measures (ECMs) in the building, and then as part of the savings determination procedure. The simulation tool applied in this study was DOE2.1E developed by Lawrence Berkeley National Laboratory [13].

Contributed by the Solar Energy Division of THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS for publication in the ASME JOURNAL OF SOLAR ENERGY ENGINEERING. Manuscript received by the ASME Solar Energy Division, March 2001; final revision, Jan. 2003. Associate Editor: G. Vliet.

Calibration Methodology

A stepwise procedure is needed for a robust approach to calibration of computer models of building energy performance. Figure 1 shows the seven step process established in this study to calibrate a model with sub-metered monthly data. Following this process, a sound model can be obtained and more reliable ECM evaluation is possible in the audit phase. The calibration process utilizes the key concept of a detailed base load consumption determination with the swing-season base load analysis recommended by Lyberg [14]. These steps use sub-metered data and site visits to disaggregate the non-weather dependent energy use in the building. The process concludes with the incorporation of detailed operating characteristics obtained from site measurements and operator interviews. The calibration method uses the following steps:

1. Base case modeling
2. Base load consumption analysis
3. Swing-season calibration
4. Site interview and measurements
5. Heating and cooling season calibration
6. Validation of calibrated base model

The calibrated model may then be used to evaluate ECMs as step 7. Example plots used to illustrate the steps taken are based on the calibration process for an 83,212 m^2 commercial building located in downtown Seoul.

Step 1: Base Case Modeling. The first step is to collect the building data, utility data, and weather data needed for simulation. This study used a PC version of DOE2.1E. This program requires input of information on as-built building geometry, HVAC system data, and operating data. This also includes site review for reliability of uncertain variables, such as peak internal gain level and the schedule of internal gains. Zoning should be done carefully based on the design drawings and actual divisions between core and perimeter spaces. Utility records and hourly weather data from a local weather station must be obtained for the calibration period. The weather data must be processed into a format compatible with the simulation program [8]. Creating the inputs for building geometry and zoning is time consuming and input errors are common. Visualization software can help minimize errors during this step [15]. The base case simulation is run using the set of inputs collected during this phase.

Step 2: Base Load Consumption Analysis. The next step is to analyze the base load electricity and gas consumption using a combination of utility bill analysis and short-term sub-metered data. (Note that the term *base load* as used in this paper refers to the minimum, or weather independent electricity or gas consumption, analogous to the base load on a power plant, not to the design heating or cooling load on the building). First, the total electricity consumption including the cooling consumption is plotted as a function of monthly average outdoor temperature as shown in Fig. 2. This figure uses four years of billing data for 1991–94 normalized to average daily consumption during each billing period. A 3-P model [16,17] shows the non-weather dependent base load consumption to be 37.1 MWhr/day and also shows the cooling change-point temperature is 13°C. Figure 3 shows the corresponding plot of average daily gas consumption for the case study building. The gas consumption is zero above the heating change-point temperature of 13°C. These figures provide values for the base-level loads and the detailed analysis of base load consumption is based on use of short term measurement data as shown in Fig. 4.

Short time hourly measurements for at least a day and preferably for a week or more are required to separate the usage into the important end uses. Most buildings in Korea are equipped with several watt meters to monitor the electricity for various uses, such as lighting, cooling, plug-loads, elevators, etc. The uses recorded by each watt-meter must be determined by examining the electrical diagrams, supplemented by a site survey and interviews with the mechanical operating staff. A data-logging sheet may be used to collect the electricity consumption for one or more days from each watt-meter. While cost and convenience suggest using only this data, it may be necessary to supplement these measurements with portable meters to accurately separate all end uses needed. Figure 4 illustrates the procedure by which the site visit and interview were used to further separate the measurements obtained from the 15 meters in the case study building. These values were then recombined to produce the pie chart containing the electricity use for the major load categories: lighting, HVAC equipment, plug-loads, and elevators. The daily consumption total of 33,980 kWhr from these measurements is within a few percent of the base load consumption of 37,303 kWhr/day determined in Fig. 2. It may also be used to tune the computer models of lighting, cooling, plug-load, and elevator use for the swing-season calibration. It is also important to carefully determine schedules for weekend days during this phase. The base load consumption shown in Fig. 4 can be extended to a monthly value of about 1019 MWhr/month. The lighting, cooling, plug-load, and elevator uses are 31%, 16%, 41%, and 12%, respectively, based on the collected data. The heating and cooling shown in Fig. 4, as part of the base load, corresponds to fan and pump energy plus that consumed by some heat pumps and packaged air conditioning units, which are

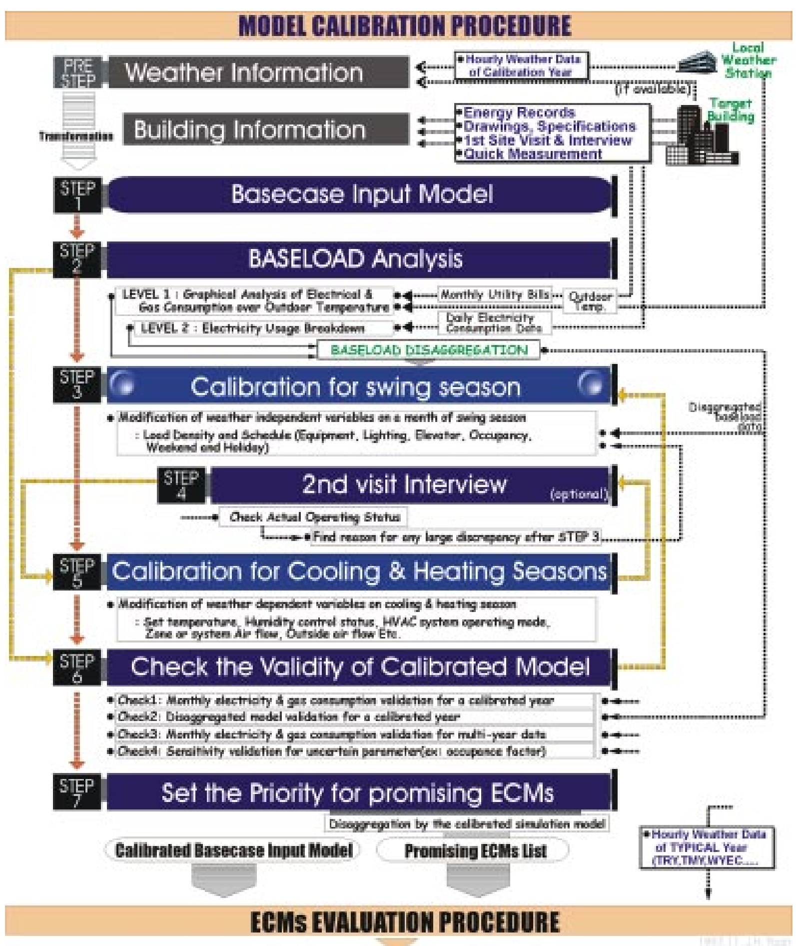

Fig. 1 Seven step calibration procedure including base load consumption analysis

used to dissipate internal gain independent of outside temperature. The internal gain intensity per unit area can be obtained and validated with this method.

Step 3: Swing-Season Calibration. The verified internal gain levels can then be used during the swing-season calibration. The swing-season calibration fine tunes a number of simulation inputs when heating and cooling loads are minimal and building behavior is dominated by internal loads. The key tuning parameters during this step are lighting, HVAC equipment, plug load, and elevator consumption, which were determined in the previous step. The calibration process then fine-tunes magnitudes (portions of measured consumption, such as motors outside conditioned space may not contribute to zone loads) and schedules for these inputs for both working and non-working days until the differences between the predicted and the measured heating and cooling consumption satisfy a specified limit. Site visits to confirm these schedules and other changes may be necessary for input validation during this step.

Step 4: Additional Site Visits and Interviews. Additional site visits and interviews are one of the most important steps in the process. These visits often refine the lighting density, quantities of office equipment like computers and printers, the name plate consumption of this equipment, and the number of occupants, and their schedule. In general, any errors or uncertainty in the internal gain levels and operating schedule affects the accuracy of the model in the next step, since these are typically the most influential load determinants. The site review checks power densities of equipment and occupancy load by observation and watt measurements. Conversations with the mechanical staff help revise the schedules of weekday and weekend operation. The density and schedule of the elevators was checked to improve the model accuracy in this study. In practice, monthly model prediction within 10% of measured consumption has been considered acceptable for a calibrated model [3,4].

Step 5: Heating/Cooling Season Calibration. The next step of the cooling/heating calibration should be carried out when the differences were less than the specified values in the swing-season calibration. A careful review should be made of all important HVAC settings, such as hot deck and cold deck set temperatures, schedules, the control algorithms employed, HVAC system operating characteristics, and outdoor air used. The overall efficiency and the part load performance of the HVAC cooling and heating equipment are also very important. One should check all default values used to see if there are any differences from the actual conditions. Otherwise, another site visit may be required if the differences between simulated and measured performance for monthly totals or the individual days for which data are available exceed 10%. This site visit should focus on ensuring that the HVAC system and plant parameters used in the simulation correspond to those actually measured in the building.

Step 6: Validation of Calibrated Model. Finally, a calibrated model can be developed from the base load and heating/cooling consumption analysis. Previous investigators have found it possible to achieve agreement of 5–15% between simulated and measured quantities, depending on the level of measurement available [3,10]. It is quite desirable to use numerical comparisons as well as graphical comparisons to determine when a simulation is adequately calibrated. The statistical Mean Bias Error (MBE) between measured and simulated consumption is one important measure of model calibration. This approach has the disadvantage that large compensating errors can lead to a zero MBE. Therefore, the Root Mean Squared Error (RMSE) and the Coefficient of Variation (CV) of the root mean squared error values are often used as well [18]. These three measures are defined as follows:

$$\mathrm{MBE}=\frac{\sum_{i=1}^{n}(Q_{pred,i}-Q_{data,i})}{nQ_{data}}$$

$$\mathrm{RMSE}=\frac{\sqrt{\Sigma(Q_{pred,i}-Q_{data,i})^2}}{n}$$

$$\mathrm{CV(RMSE)}=\frac{\mathrm{RMSE}}{Q_{data}}=\frac{\dfrac{\sqrt{\Sigma(Q_{pred,i}-Q_{data,i})^2}}{n}}{Q_{data}}$$

where, MBE: Mean Bias Error

RMSE: Root Mean Squared Error

CV(RMSE): Coefficient of Variation of the root mean squared error

$Q_{pred,i}$: predicted value during period i

$Q_{data,i}$: measured value during period i

Q_{data}: measured avg during the period

We recommend that these measures be used in combination, seeking low values of each measure.

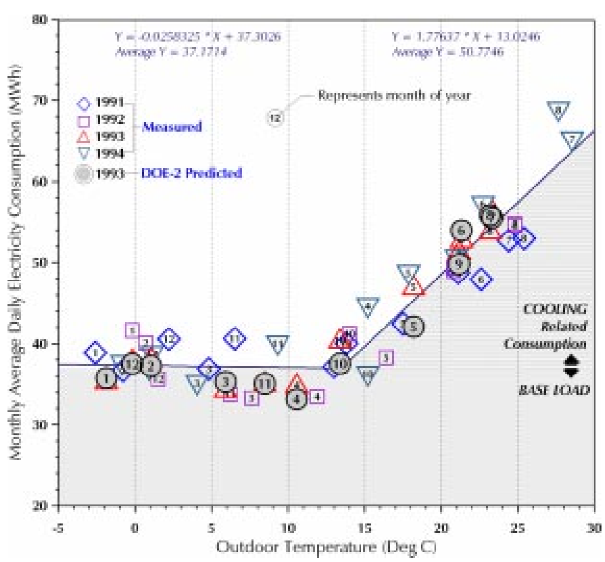

Fig. 2 Base load consumption and cooling consumption characteristic curve

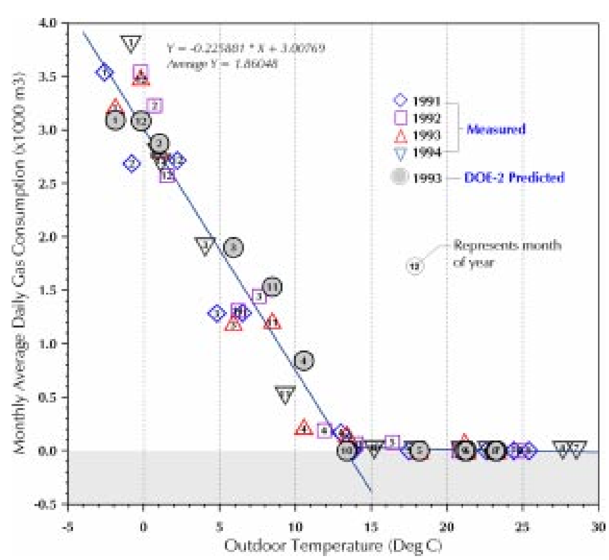

Fig. 3 Characteristic temperature behavior of building heating (gas) consumption

A Box-Whisker-Mean approach, showing the maximum, average, and minimum values [19] from actual multi-year energy records is also very effective in illustrating the validity of a simulation model.

Step 7: Application of Calibrated Simulation Model to Investigation of Promising ECM's. When using a calibrated simulation model to investigate ECMs, it is very important to disaggregate the energy consumption by end uses as illustrated in Fig. 4. This provides the energy auditor with a valuable and powerful tool for identifying promising, building specific ECMs. The possible ECMs can then be prioritized based on those impacting end uses with maximum consumption relative to good practice. The potential savings of ECMs may then be evaluated using the calibrated simulation model, with confidence that construction and implementation will result in savings similar to those simulated. The interactions of multiple ECMs can also be accurately determined. Use of the calibration procedure will be demonstrated in the following case study.

Case Study

A case study to demonstrate the methodology has been performed for a large commercial building located in downtown Seoul. The target building has 26 stories and four underground floors, with most floors having an area of 3,920 m^2. The total floor area of the building is 83,212 m^2. The building is equipped with a centrifugal chiller and an ice storage system for cooling and with a LNG gas boiler for heating. The real weather data for the year 1993 was converted into the TRY format for use in the DOE2.1E weather input file [20]. The system and the plant were then modeled with the DOE2.1E program using the actual data from 1993, and the measured data was used to calibrate the model. Weather data for 1991, 1992, and 1994 were later used to see how well the model was calibrated in these years (see Fig. 5 and discussion). The base load analysis procedure was used to tune the model. Figures 2 and 3 show that cooling and heating consumption exhibit very clear 3-parameter piece-wise linear behavior as a function of the outdoor temperature. Figure 4 shows the end-use results developed from measured data as described previously. A careful review must be conducted to verify/determine the internal load density and schedule for weekdays and for weekend days. One typical week day was selected based on the daily measured data as shown in Figure 4, and a typical weekend day was also selected using the same process. A number of iterations may be needed to match the predictions and the key measured elements.

Figure 5 shows the results of thirteen simulations used to calibrate the simulation model. Run01 used the inputs for the base case collected in step 1. Run02 modified the elevator loads according to the findings of step 2 while Run03 used the inputs of Run01 modified to incorporate the plug loads and schedules from step 2. Run04 changed the lighting loads from step 1 to step 2 and Run05 corrected the internal occupancy density and schedule. Run06 incorporated all the changes made from Run02 to Run05 simultaneously and corresponds to the swing season calibration of

Site Visit and Interview Note for Electricity Disaggregation & Estimation

Watt-meter No.	Measured Electricity kWh/day		Electricyty Consumption Components (Site visit and Interview with building operators)
1	960		Pumps(hot water, service water, waste water, AHU etc.) : 365days 5am-5pm (AHU Schedule ; 5am-5pm, 11.25kw/floor
2	1,550		Package-type airconditioner, 3phase 220V (1set / every 3floors)
3	3,350		Lighting : Lighting Schedule 5am-8pm(100%), -10pm(60%), -12pm(40%), -5am(30%) / (Lighting Fixtures : 300units/floor)
4	3,050	2,950	Plug-Load(Computer, Office Equipment etc.)
		100	Fancoil Electricity(45Watt*58units/floor)
5	3,600		[Plug-Load]
6	5,740	1433	Computer Room(8th floor) : 24hr running, monthly 43000kWh consumption.
		2667	Computer Room(3rd floor) : 24hr running,, monthly 80000kWh consumption
		1680	Elevator : 35kw*8units*12h*50%
		1152	Emergency Lights : 64W*50unit/floor*30floors*12hr(25days/month)
		936	Office Equipment, Telex, computer etc.(28086 kWh/month)
		1472	Computer, Office Equipment etc.
7	1,780		
		700	Emergency Elevator : 35kW*2units*20hr*50%
		1,080	Lighting : Exit lights
8	240		Computer, Office Equipment etc.
9	200		Lighting : guide light, kitchen, toilet for 27th floor
10	2,580	1680	Elevator : 35kw*8units*12h*50%
		900	AHU :11.25*(18th-27th floors)*operation_ratio
11	1,070		Pumps : Cooling tower(5kw*4units for summer) etc.
12	3,780		[Plug-Load]
		2,650	Computer, OA etc.(around 100A --> 130kWh/hr)
		1130	Broadcasting Equipment (around 80A -->47kWh/hr)
13	2,900		Lighting : Schedule 5am-8pm(100%), -10pm(60%), -12pm(40%), -5am(30%)
14	490		Computer, Office Equipment etc.
15	690		Heat Pumps for Top floor(4hr-16hr 365days operation, 4units)
Daily Total		33,980	kWh/day
Monthly Total(estimate) :			*30days = 1019 MWh/month

Category of Electricity Use

Component	Electricity C. (kWh/day)		Ratio
Lighting	8,250	10,682	31%
	2,432		
Heating &	4,270	5,270	16%
Cooling	1,000		
Plug-load		13,968	41%
Elevator		4060	12%
	(SUM)	33,980	100%

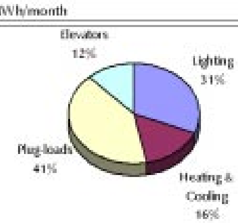

Fig. 4 Disaggregation worksheet sample for building base load consumption analysis

step 3. Runs 07-10 took the inputs of Run06 and individually added the additional changes to be described. Run07 incorporated different weekend schedules (step 4), while Run08 modeled the shopping mall in the basement using updated heating and cooling loads from the year of calibration. Run09 modeled the fresh air introduction rate based on data collected during the site visit and Run10 modified the air flow rate for each HVAC zone to match the model with the actual data more closely (Step 5). The building was designed to provide winter humidification to 40% relative humidity, but the growing relationship with the operators led them to reveal during the second site visit that the humidity control was disabled, so Run11 incorporated this change. Run12 incorporated site measured data in place of the default part-load chiller efficiencies. Finally, the base model was developed from Run13, which incorporated site measured part-load boiler efficiency data. The base model was justified with monthly gas data and electric data as shown in Fig. 6. Table 1 summarizes the impact of those 13 changes on annual energy consumption in terms of MBE and CV(RMSE). The final simulation gave annual MBE of 2.3% and CV of 3.6% for the monthly data.

Run11 indicated that the removal of winter humidity control reduced the error significantly. The 15.8% and 22.7% MBE and CV values were the lowest we could reach for gas calibration due to the uncertainties of the boiler maintenance schedule. The heating performance model has higher error values, but predicted the actual data very closely in the peak heating months. The errors occurred during the transition months when boiler maintenance was carried out, and information needed to accurately model this period could not be obtained from operating personnel.

Figure 6 compares the monthly measured gas and electricity consumption for 1993 with the values simulated by the calibrated model using 1993 weather data. The electricity model may be considered sound and valid because it has less than 3% error in

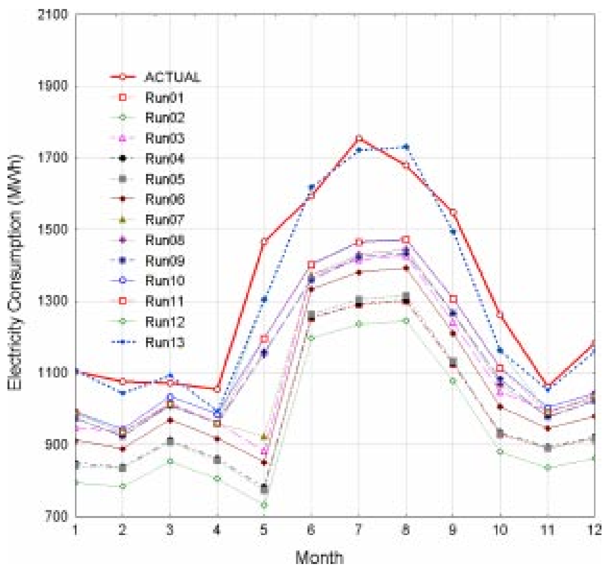

Fig. 5 Results of 13 sensitivity simulations used for base model development in the calibration process

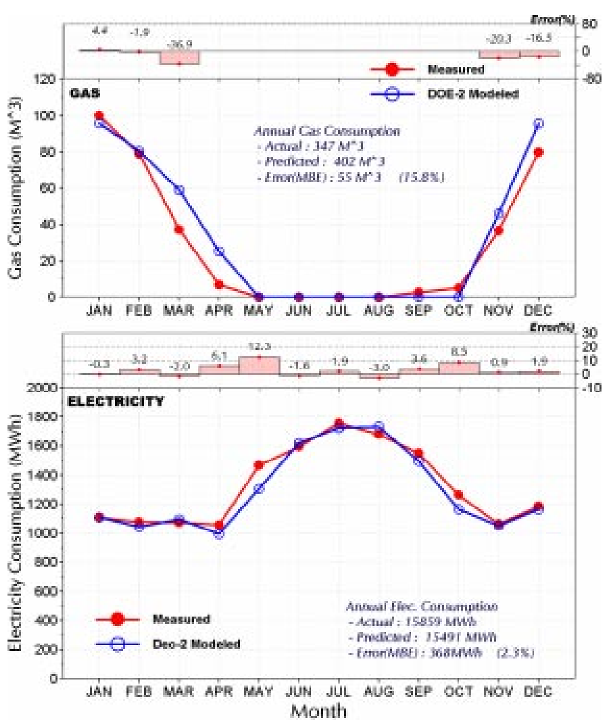

Fig. 6 Base model justification with monthly data for the case study

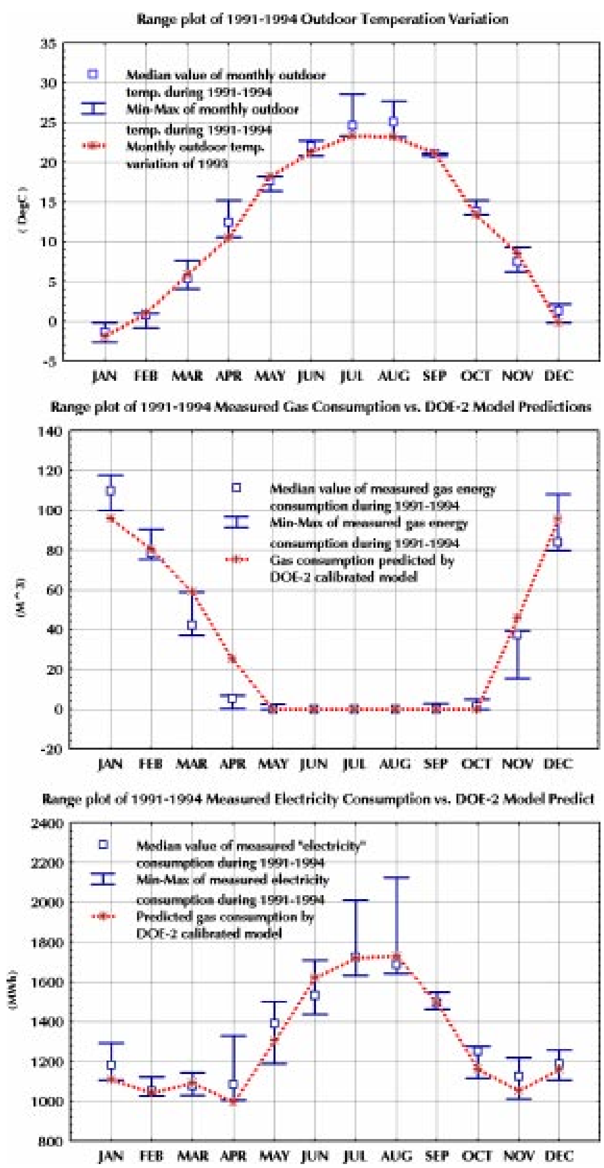

Fig. 7 Statistical verification of base model using multi year energy consumption records

Table 1 Thirteen sensitivity simulations for base model development

RUN #		Error	Electricity	Gas	Calibration Note	Related Step
(01)	01smbNZ	MBE	24.9%	−115.6%	Basecase Input Model	Step 1
		CV	24.9%	120.0%	based on Prestep	
(02)	02nzlNel	MBE	28.7%	−115.6%	Elevators Load	Step 3
		CV	28.7%	120.0%	(Power & Schedule)	
(03)	02nzlNeq	MBE	16.3%	−103.2%	Plug Loads	Step 3
		CV	16.3%	107.6%	(Density & Schedule)	
(04)	02nzlNli	MBE	24.5%	−116.4%	Lighting Load	Step 3
		CV	24.5%	120.8%	(Density & Schedule)	
(05)	02nzlNoc	MBE	24.5%	−113.2%	Occupancy Load	Step 3
		CV	24.5%	117.7%	(Density & Schedule)	
(06)	02nzlNTG	MBE	19.4%	−101.3%	Combined Effect	Step 3
		CV	19.4%	105.7%	of Run2-Run5	
(07)	03inWEse	MBE	15.6%	−95.5%	Weekend & Holiday	Step 3
		CV	15.6%	99.9%	(Density & Schedule)	
(08)	04weOTim	MBE	14.2%	−84.4%	Each Zone Set Temp. &	Step 4 &
		CV	14.2%	88.8%	Conditioning Schedule	Step 5
(09)	05otOAsy	MBE	14.3%	−68.3%	HVAC System level	Step 4 &
		CV	14.3%	72.8%	Flow Rate	Step 5
(10)	06oaCFmd	MBE	12.0%	−107.6%	Zone level	Step 4 &
		CV	12.0%	112.0%	Flow Rate	Step 5
(11)	07cfRHct	MBE	12.5%	−15.8%	Humidity control	Step 4 &
		CV	12.5%	22.7%	strategy	Step 5
(12)	08rhBrc	MBE	5.7%	−15.8%	Chiller system	Step 5
		CV	6.7%	22.7%	efficiency	
(13)	09eiBrb	MBE	2.3%	−15.8%	Boiler system	Step 5
		CV	3.6%	22.7%	efficiency	

Table 2 Model verification and validation with measured and predicted disaggregated data

Measured Electricity (March)				Simulated Elec.	(March)		
Component	kWhr/day	Ratio		Component	MWhr/month	Ratio	
Lighting	10,682		31%	Area Light	332		30%
Plug-loads	13,968	41%	53%	Internal Loads	527		48%
Elevators	4,060	12%					
Heating & Cooling, Equipment	5,270		16%	Heating	115	11%	22%
				Pumps	9	1%	
				Fans	112	10%	
SUM	33,980		100%	SUM	1,095 MWhr		100%
Baseload Range: 1023 MWhr+−7%				Baseload difference	7%		

(Related Step: Step 6, Check 2)

the cooling season months of July and August and differs by less than 10% except for May. It predicts quite closely in March and April of the swing season with errors of about 2% and 6%. The electricity comparisons for March and April show the model predicted 1095 MWhr for March and 991 MWhr for April, which is within the error bound of 7% of 1023 MWhr as shown in Table 2. Table 2 compares the monthly measured and simulated values of electricity base load. The percentages of the base load (swing season) end use components used in a day and in a month appear to be consistent, with 31% for lighting, 53% for plugs and elevators, and 16% for HVAC equipment. The model also predicts the key internal loads such as lighting and plug-loads well within the allowable error range. The heating predictions are within 4% during the peak heating season, and while overall model predictions for heating are not as close as those for cooling due to the unknown operating conditions during boiler maintenance, heating also represents a smaller portion of the operating cost than cooling. Hence we conclude that the model is well calibrated.

Figure 7 compares the monthly electricity and gas use predictions of the final calibrated model with the measured monthly consumption for 1991–94 and compares the average monthly temperatures for the 1993 data used as input to the simulation with the values for 1991–94. The solid vertical lines extend from the minimum to the maximum value of the quantity plotted while the open squares show the mean value of the monthly totals measured during the four years. The outdoor temperature curve of Figure 7 shows that the 1993 data used in the simulation was quite close to the mean value for every month in the 4-yr period. The simulation based on the data for 1993 similarly predicted the electricity and gas consumption quite close to the mean consumption for each month during this period except for swing season gas consumption during March, April, and November. A portion of this discrepancy is accounted for by boiler shutdown for maintenance, but a portion of this discrepancy has not been explained. The values of electricity and gas consumption shown in Fig. 7 provide a strong basis for confidence that the calibrated model will accurately evaluate the potential savings that may result from ECMs implemented in this building. More details on the calibration process and results are available in a KIER [21] technical report.

The level of effort required for this calibration was approximately 17 person-days, not including procedural development. This effort included about eight days for the initial modeling through step 1, about 2 days for base load analysis with submetered data in step 2, and 5–7 days for steps 3–7.

Conclusions

The number of energy audit projects on larger buildings in Korea is increasing because many buildings were constructed in the mid-1970s before energy efficient designs were considered in Korea. A key element in the energy audit and retrofit process is the accurate quantification of the energy savings potential through the audit. The calibration process developed and demonstrated in this paper can be used to project the savings from retrofit measures and then used as a key element in the savings determination process. Option D of the International Performance Measurement and Verification Protocol [22] specifies the use of a calibrated computer simulation to quantify the savings from the retrofit.

The base load sensitivity simulations performed in this study found the internal gain to be a major parameter impacting the building energy performance. The impact has been confirmed and visualized with the measured data from the building site. A unique way of calibrating the computer model specially with the base load, non-weather dependent data, has been proposed and justified in this study. Due to the relative complexity and cost of hourly measurements, calibration with monthly sub-metered data has been proposed and justified with an actual case study for a building located in Seoul. This method may be considered as a more realistic way of using the typical watt-meters with which most buildings in Korea are equipped.

Korea is now starting to focus on energy consulting to overcome the economic crisis of 1998. The government has instituted an Energy Service Company (ESCO) funding policy to support the energy saving business in Korea. One option within this government policy requires a computer simulation to quantify the energy savings from promising ECMs. The proposed calibration method may be used effectively to establish the base case and justify the estimated savings for the selected ECM conditions.

References

[1] Diamond, S., and Hunn, B., 1981, ''Comparison of DOE-2 Computer Program Simulations to Metered Data from Seven Commercial Buildings,'' ASHRAE Trans., **87**(1), pp. 1222–1231.

[2] Holtz, M. 1990, ''Electrical Energy Savings in Office Buildings,'' Technical Report of Swedish Council for Building Research, ISBN 91-540-5213-0.

[3] Kaplan, M., Mcferran, J., Jansen, J., and Pratt, R., 1990, ''Reconciliation of a DOE2.1c Model with Monitored End-Use Data from a Small Office Building,'' ASHRAE Trans., **96**(1), pp. 981–993.

[4] Pratt, R. G., 1990, ''Errors in Audit Predictions of Commercial Lighting and Equipment Loads and Their Impacts on Heating and Cooling Estimates,'' ASHRAE Trans., **96**(1), pp. 994–1000.

[5] McCray, J. A., Bailey, P. L., and Parker, J. L. 1995, ''Using Data Visualization Tools for the Calibration of Hourly DOE-2.1 Simulation,'' *Building Simulation '95, Int. Building Performance Simulation Assoc., 4th Int. Conf.*, pp. 461–466.

[6] Bou-Saada, T. E., and Haberl, J. S. 1995, ''An Improved Procedure for Developing Calibrated Hourly Simulation Models'' *Building Simulation '95, Int. Building Perform. Simul. Assoc. 4th Int. Conf.*, pp. 475–484.

[7] Bronson, D. J., Hinchey, S. B., Haberl, J. S., and O'Neal, D. L., 1992, ''A Procedure for Calibrating the DOE-2 Simulation Program to Non-Weather-Dependent Measured Loads,'' ASHRAE Trans., **98**(1), 636–652.

[8] Haberl, J. S., Bronson, J. D., and O'Neal, D. L., 1995, ''An Evaluation of the Impact of Using Measured Weather Data Versus TMY Weather Data in a DOE-2 Simulation of an Existing Building in Central Texas,'' ASHRAE Trans., **101**(1), pp. 558–576.

[9] Haberl, J., and Bou-Saada, T., 1998, ''Procedures for Calibrating Hourly Simulation Models to Measured Building Energy and Environmental Data,'' ASME J. Sol. Energy Eng., **120**(3), pp. 193–204.

[10] Liu, M., and Claridge, D. E., 1998, ''Use of Calibrated HVAC System Models to Optimize System Operation,'' ASME J. Sol. Energy Eng., **120**, pp. 131–138.

[11] Liu, M., Wei, G., and Claridge, D. E. 1998, ''Calibrating AHU Models Using Whole Building Cooling and Heating Energy Consumption Data,'' *Proc. of ACEEE 1998 Summer Study on Energy Efficiency in Buildings*, **3**, American Council for an Energy Efficient Economy, Washington, D.C., pp. 229–241.

[12] Reddy, S. N., Hunn, B. D., and Hood, D. B. 1994, ''Determination of Retrofit Savings Using a Calibrated Building Energy Simulation Model,'' *Proc. of 9th Symp. on Improving Building Systems in Hot and Humid Climates*, Arlington, TX, pp. 153–165.

[13] LBNL, 1982, ''*DOE-2 Reference Manual*,'' Lawrence Berkeley Laboratory and Los Alamos National Laboratory, Report No. LBL-8706 Rev. 2.

[14] Lyberg, M. D. 1987, *Source Book for Energy Auditors*, IEA Energy Conservation, Swedish Council for Building Research, Stockholm, Sweden, (ISBN: 91-540-4763-3).

[15] Huang, J. 1993, *DrawBDL User's Guide*, Joe Huang and Associates, DrawBDL Version 1.03.

[16] Fels, M., 1986, ''Special Issue Devoted to Measuring Energy Savings, The Scorekeeping Approach,'' Energy Build., **9**(1,2), pp. 1–180.

[17] Kissock, K., Reddy, T. A., and Claridge, D. E., 1998, ''Ambient-Temperature Regression Analysis for Estimating Retrofit Savings in Commercial Buildings,'' ASME J. Sol. Energy Eng., **120**(3), pp. 168–176.

[18] Kreider, J. F., and Haberl, J. S., 1994, ''Predicting Hourly Building Energy Use,'' ASHRAE Trans., **100**(2), pp. 1104–1118.

[19] Haberl, J. S., and Abbas, M., 1998, ''Development of Graphical Indices for Viewing Building Energy Data: Part I,'' ASME J. Sol. Energy Eng., **120**(3), pp. 156–161.

[20] Kim, K. S., Yoon, J. H., and Lee, E. J. 1998, ''A Study on Seoul Weather Data for Building Energy Audit,'' *13th Workshop on Energy Conservation Technology*, Yusong, Korea.

[21] Kim, K. S., Yoon, J. H., and Lee, E. J. 1997, ''Development and Application of Advanced Energy Performance Assessment Technology for Building Energy Management,'' KIER Tech. Report, 1997. 11.

[22] IPMVP, 1997, *International Performance Measurement and Verification Protocol*, U.S. Department of Energy, DOE/EE-0157, Washington, DC.